PROCEEDINGS OF SCIENCE

Neutrino properties, mass hierarchy and CP-violation

Alexei Y. Smirnov[*]

Max-Planck-Institute for Nuclear Physics, Heidelberg, Germany
E-mail: `smirnov@mpi-hd.mpg.de`

All what we know about neutrinos with high confidence fits well the three-neutrino paradigm: 3 massive and mixed neutrinos with interactions described by the Standard Model. The paradigm is challenged by possible existence of new neutrino species - sterile neutrinos and new ("non-standard") interactions. The big unknowns include the type of neutrino mass ordering (hierarchy) and value of the CP-violation phase. Possibilities to determine these unknowns using the astrophysical and atmospheric neutrinos are described. Future large under-ice/water detectors of the atmospheric neutrinos PINGU and ORCA, have good chance to determine the hierarchy first. The hierarchy can also be established from analysis of Galactic supernova neutrino bursts. Although it is believed that the CP phase will be measured using accelerator neutrinos, a possibility should be explored to determine the phase using atmospheric neutrinos and upgrades of PINGU and ORCA with low energy threshold, $E_{th} = (0.5-1)$ GeV.

ICRC 2015,
July 27- August 6 2015
Hague, The Netherlands

---

[*] Speaker.

PoS(ICRC2015)004

1. Introduction

Content of this review follows the title. Neutrino properties: I will present brief summary of what we know about neutrinos in sect. 2. The mass hierarchy determination is probably the next big in neutrino physics (sect. 3). Discovery of CP-violation in the lepton sector and measurements of the Dirac CP-phase discussed in sect. 4, are ultimate goals of neutrino oscillation studies. While from theoretical point of view it is not clear how the hierarchy and CP phase are related, their measurements are connected in various ways. An emphasis will be made on astrophysical and astroparticle methods.

2. Neutrino properties

The $3\nu-$ paradigm: all well established and confirmed results fit a framework of

- three neutrinos
- with masses and mixing and
- interactions described by the Standard Model.

It is widely believed that peculiar properties of neutrinos (i) smallness of masses, (ii) large mixing, and (iii) zero values of conserved (electric and color) charges are somehow connected. The items (i) and (ii) are probably related to the Majorana nature of neutrinos which is allowed by (iii).

Let us summarize the main features of the neutrino mass and lepton mixing.

1. The mixing is described by the PMNS matrix, U_{PMNS}, which connects the flavor neutrino states $\nu_f = (\nu_e, \nu_\mu, \nu_\tau)^T$ and the mass states $\nu_{mass} = (\nu_1,\ \nu_2,\ \nu_3)^T$ as

$$\nu_f = U_{PMNS}\nu_{mass}. \tag{2.1}$$

In the standard parametrization:

$$U_{PMNS} = U_{23}(\theta_{23})\Gamma_\delta U_{13}(\theta_{13})\Gamma_\delta^* U_{12}(\theta_{13}), \tag{2.2}$$

where $\Gamma_\delta \equiv (1, 1, e^{-i\delta})$. The element of PMNS matrix, $|U_{\alpha i}|^2$, determines admixture of the $\alpha-$ flavor ($\alpha = e,\ \mu,\ \tau$) in $i-$ mass eigenstate. The mixing angles in (2.2) have the following meaning (see Fig. 1): $\tan^2\theta_{12} = |U_{e2}|^2/|U_{e1}|^2 \sim 0.5$ fixes relative distribution of the ν_e- flavor in the second and the first mass states; $\sin^2\theta_{13} = |U_{e3}|^2 \approx 0.022$ is the admixture of the ν_e flavor in the third mass state, and $\tan^2\theta_{23} = |U_{\mu 3}|^2/|U_{\tau 3}|^2 \approx 1$ gives relative contribution of the $\nu_\mu-$ and $\nu_\tau-$ flavors to the third state.

2. In the first approximation the lepton mixing has the tribimaximal mixing (TBM) pattern [1]:

$$U_{PMNS} \approx U_{TBM} = \begin{pmatrix} \sqrt{\frac{3}{2}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}. \tag{2.3}$$

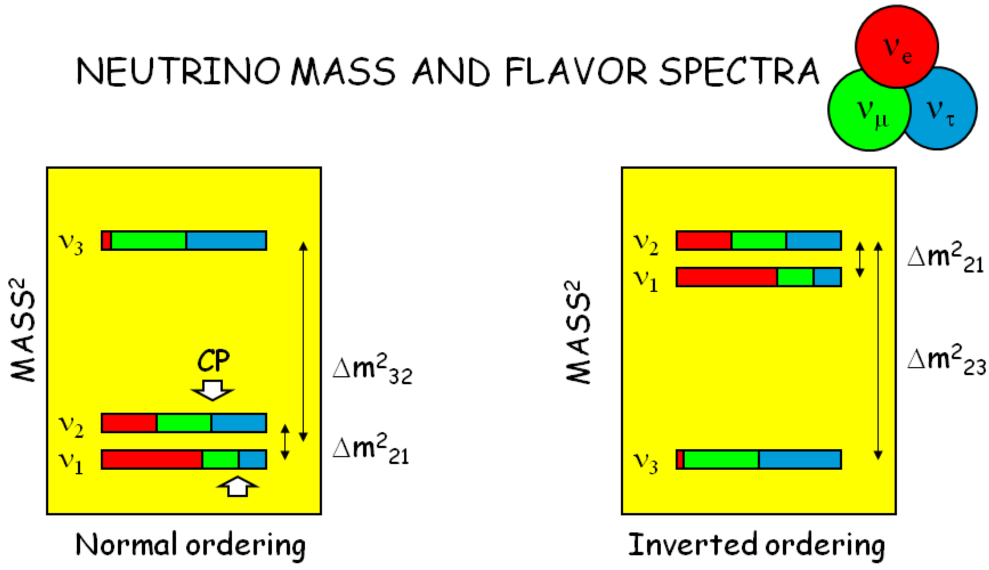

Figure 1: Neutrino mass and flavor spectra for normal (left) and inverted (right) mass hierarchies. If the length of boxes are 1, the colored parts give $|U_{\alpha i}|^2$.

There are two points of view: (i) The equality (2.3) is accidental, numerology being useful for bookkeeping. (ii) The relation (2.3) is not accidental, but appears as the lowest order approximation which corresponds to weakly broken flavor symmetry of the Lagrangian. In this case one expects some other physics consequences as well as structures of theory that can be tested in future experiments like, e.g., new Higgs bosons with certain couplings.

3. Neutrino mass ordering is know only partially. The order of states 1 and 2 in mass scale is fixed by the solar neutrinos if no new physics is present [2]. The 1-3 mass ordering is an open issue. The two orderings (see Fig. 1) differ by the total sum of neutrino masses and by relation of mass squared differences. In the “normal" case (left) $\sum_i m_i \geq m_h = m_3$, and

$$|\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|, \tag{2.4}$$

whereas in the “inverted" case: $\sum_i m_i > 2m_h \approx 2m_2$ and

$$|\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|. \tag{2.5}$$

The mass splittings in these equalities are associated to (can be marked by) oscillation depths:

$$\Delta m^2_{ij} \leftrightarrow D_{ij} = 4|U_{ei}|^2|U_{ej}|^2.$$

In particular, $D_{13} = 2D_{23}$.

4. Global oscillation fit [3] uses data from experiments with solar neutrinos (including recent BOREXINO and SK results), atmospheric neutrinos (SuperKamiokande, DeepCore, Antares), reactor neutrino experiments (Double CHOOZ, DayaBay, Reno), accelerator experiments (MINOS, T2K, NOvA). The data are interpreted using essentially two effects: oscillations in vacuum and in matter, and the adiabatic flavor conversion (the MSW effect). The outcome of the fit is values of

mass squared differences, Δm^2_{ij}, mixing angles θ_{ij}, and the CP-phase δ_{CP}. Notice that number of experimental results is larger than the number of parameters, and so the “system" is overdefined. In this way one can make cross-check of results. Furthermore, different experiments being sensitive to the same parameters have different environment (e.g., vacuum and dense matter) which provides sensitive way to search for new physics. The fact that results from different experiments are in a good agreement allows to put bounds on new physics and to test theory of neutrino propagation and conversion.

Few comments on results of the fits are in order.

- the 1-3 mixing determination is dominated by the Daya Bay accuracy [4], and the result is supported by RENO [5] and Double Chooz [6]. Interestingly, the value of angle continuously decreased with time in comparison with the initial measurements. (Is this systematics related to change of characteristics of scintillators?)

- values of $\sin^2\theta_{12} = (0.30 - 0.31)$ and Δm^2_{31} are rather stable, and recently Δm^2_{32} has been measured by reactors and by Deep Core experiment (Fig. 2).

- Δm^2_{21} is determined by KamLAND [9]. Solar neutrinos (having lower accuracy) give about 2σ smaller value [10]. KamLAND has no front detector. Certain new features of the reactor neutrino flux have been realized recently, in particular, bump at (4 - 6) MeV [4], [5], [6], which have not been taken into account previously. Therefore the KamLAND data should be re-analysed. It has been estimated [10] that the bump leads to small decrease of Δm^2_{21}, thus slightly improving the agreement.

- $\sin^2\theta_{23}$ has the biggest uncertainty with two aspects: (i) Deviation from maximal mixing, which is the key issue for existence of symmetry, and (ii) octant of the angle: in the case of normal ordering the first octant is preferable with $\sin^2\theta_{23} = 0.45$, whereas for the inverted ordering (IO) the second quadrant with $\sin^2\theta_{23} = 0.58$ gives better fit.

The new exciting result is about the CP-phase: the T2K detects large number of ν_e events [11] which can be reconciled with the reactor measurements of the 1-3 mixing if CP violation is maximal: $\delta_{CP} = -\pi/2$. This result is also confirmed by global fits, and recently, – by the first NOvA result.

Large atmospheric neutrino detectors, DeepCore and ANTARES are new players in the oscillation game. Amazingly, just after 3 years of operation DeepCore gives competitive accuracy of measurements of the 2-3 mixing and mass splitting (Fig. 2).

5. Absolute neutrino mass scale. Oscillations give the lower bound on mass of the heaviest neutrino: $m_h \geq \sqrt{\Delta m^2_{31}} = 0.045$ eV. Furthermore, the ratio of masses in the case of normal mass ordering equals

$$\frac{m_2}{m_3} \geq \sqrt{\frac{\Delta m^2_{21}}{\Delta m^2_{31}}} \approx 0.18. \tag{2.6}$$

Thus, the neutrinos have the weakest mass hierarchy among leptons and quarks.

Cosmology gives the bound on the sum of neutrino masses

$$\sum_i m_i < 0.136 \text{ eV} \quad (95\%\text{C.L.}) \tag{2.7}$$

based on combined analysis of data from Planck 2015, BAO and HTS [12]. Conservative bound, $\sum_i m_i < (0.3 - 0.4)$ eV, leads to $m(\nu_e) < 0.10 - 0.13$ eV, which is stronger than the upper bound

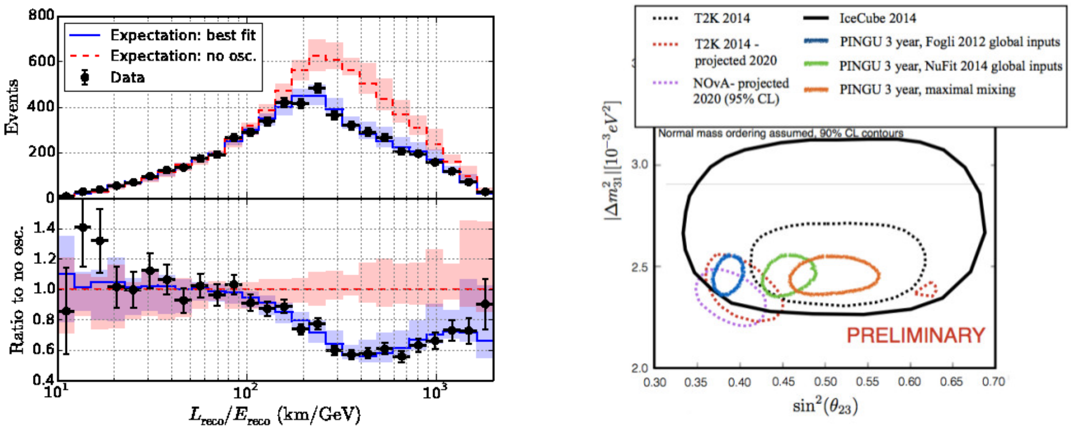

Figure 2: DeepCore oscillation result and projected future sensitivity. Left: L/E dependence of number of events, and ratio of events with and without oscillations [7]. Right: The allowed region of the 2-3 oscillation parameters [8]. Also shown are projected sensitivities of T2K, NoVA and PINGU experiments.

$m(\nu_e) < 0.2$ eV that can be achieved by KATRIN experiment [13] (kinematic measurements of beta spectrum of tritium) which should start to operate in 2016.

It is widely accepted that there is new physics behind the smallness of neutrino mass and the observed mixing pattern which strongly differs from the quark mixing pattern. Where is this new physics? The energy scales of proposed new physics scenarios, Λ_{NP}, spread over 28 orders of magnitude: from the sub-eV up to the Planck scale.

1. The GUT-Planck mass scale appears as

$$\Lambda_{NP} = \frac{v_{EW}^2}{m_\nu} \sim \left(10^{14} - 10^{16}\right) \mathrm{GeV}, \tag{2.8}$$

where v_{EW} is the electroweak scale. It is along with the unification approach which includes the high scale seesaw [14], $m_\nu = -m_D^T M_R^{-1} m_D$, quark-lepton symmetry (analogy), GUT. Here $\Lambda_{NP} \sim M_R$ is the mass of right handed (RH) neutrinos, and m_D is the neutrino Dirac mass. In the presence of mixing the heaviest RH neutrino can be $M_3 \sim M_{GUT} \sim 10^{16}$ GeV. Alternatively, the double seesaw mechanism can relate of the RH neutrino masses with the Planck mass scale as $M_R = M_{GUT}^2/M_{Pl} = (10^8 - 10^{14})$ GeV [15].

2. In connection to the Ice Cube neutrinos, new physics at PeV scale has been proposed [16]. It can be related, e.g., to the multi-PeV mass particles of the dark matter whose decays produce neutrinos.

3. The electroweak - LHC scale, $\Lambda_{NP} = V_{EW} \div E_{LHC}$, is the most popular one. New particles at (0.1 - few) TeV scale are expected to exist which can be tested at LHC. Lepton flavor violation decays can be at the level of sensitivity of present experiments. Also testable low scale mechanisms of neutrino mass generation include the GeV - TeV seesaw, low scale Left-Right (LR) symmetry model, R-parity violating SUSY with neutralino as RH neutrino, inverse seesaw with very small ($\mu \sim$ keV) lepton violation term, radiative mechanisms with one, two, three loops, high dimensional operators, radiative see-saw, Higgs triplet with small VEV, new "neutrinofilic" Higgs doublets, *etc*.

ν MSM [17] deserves special attention in view of possible (although controversial) observation of the astrophysical 3.5 kev X-line [18] (see, however [19]) and non-observation of new physics at LHC and other experiments. In νMSM everything is below the EW scale, and correspondingly, nothing is up to the Planck scale. This implies very small neutrino Yukawa couplings. The RH sector consists of two RH neutrinos of the $(0.1-10)$ GeV mass with extremely small (below eV) splitting. These neutrinos generate masses of active neutrinos via seesaw, and the lepton asymmetry in the Universe via oscillations. They can be produced in B-decays (BR $\sim 10^{-10}$) [20]. The third neutrino with $m = 7$ keV forms the warm dark matter of the Universe and its decay $N_1 \to \nu\gamma$ produce the 3.5 keV X-line.

4. The eV - sub eV scale:

$$\Lambda_{NP} \sim m_\nu, \tag{2.9}$$

that is, the neutrino mass itself can be the fundamental scale of new physics, and not just spurious quantity made of some other scales as in see-saw. This can be related to the dark sector of the Universe, dark energy, mass varying neutrino (MAVAN) scenario [21], existence of new relativistic degrees of freedom (dark radiation).

Concerning explanation of the lepton mixing (see recent reviews [22]), the proposed approaches span from flavor symmetry to anarchy and randomness. Consistent realizations of the first approach in the gauge theories lead to complicated structures with many new fields, parameters and assumptions, especially if the quarks are also included. The second approach implies a kind of string landscape and multiverse concepts but here not much to add. There are also intermediate possibilities when symmetric structures, that appear in the first approximation, are accompanied by random perturbations. So, "symmetry or no symmetry?" is still an open issue. All in all, new physics behind neutrino mass is not yet identified.

There are various indications that the lepton (PMNS) and quark (CKM) mixing matrices are related. One intriguing possibility is that [23], [24], [25]

$$U_{PMNS} = U_{CKM}^{\dagger} U_X, \tag{2.10}$$

where $U_{CKM} \sim V_{CKM}$, *i.e.* has similar hierarchical structure determined (as in the Wolfenstein parametrization) by powers of the Cabibbo angle $\lambda \approx \sin\theta_C$. U_{CKM} emerges from the Dirac matrices of charged leptons and neutrinos. The matrix U_X is related to mechanism that explains smallness of neutrino mass and its structure can be determined by certain symmetries. One possibility is that $U_X \approx U_{23}U_{12}$ with small or negligible 1-3 mixing.

The framework (2.10) leads to relation [26], [27]

$$\sin^2\theta_{13} = \sin^2\theta_C \sin^2\theta_{23}(1 + O(\lambda^2)), \tag{2.11}$$

which is in a good agreement with experimental data. Measurements of the 1 - 3 mixing with the present accuracy disfavor at more than 3σ the lowest order relation, $\sin^2\theta_{13} = 0.5\sin^2\theta_C$ which corresponds to maximal 2-3 mixing. The corrections of the order λ^2 and deviation of 2-3 mixing from maximal one become important.

The relation (2.10), if not accidental, means that quarks and leptons ”know" about each other, it implies a kind of quark-lepton unification or common flavor symmetry in the quark and lepton sectors. At the same time, an additional physics is involved in the lepton sector which explains smallness of neutrino mass and difference of the lepton and quark mixings. Thus, two types of new physics are involved:

1. The “CKM-type" new physics, which produces the CKM mixing and (different) mass hierarchies of charged leptons and quarks.

2. The Neutrino new physics.

The relation (2.10) can be realized in the seesaw type-I mechanism. It indicates $SO(10)$ GUT [27].

Several challenges and anomalies drive further developments of the field. Namely,

1). Determination of unknown parameters within 3ν paradigm which includes mass ordering, absolute values of masses, type of spectrum (hierarchical, degenerate), CP-violation phase(s), establishing nature of neutrino mass: (Majorana-Dirac, hard versus soft).

2). Tests of anomalies and their explanations. Among them are the so called Reactor and Gallium anomalies which show a deficit of observed $\bar{\nu}_e$ signal. In contrast, the LSND and MiniBooNE anomalies show an excess of the $\bar{\nu}_e$, ν_e signals. The eV mass scale sterile neutrinos provide rather controversial explanation of the appearance anomalies. Furthermore, the eV mass scale neutrinos with the required ~ 0.1 mixing are not a small perturbation of the 3ν picture. Ice Cube experiment has potentially very high sensitivity to steriles [28], and results of analysis are very much anticipated.

Another hot spot is the “Solar neutrino tension” which involves several probably related facts: (i) absence of spectral upturn of the energy spectrum at low energies, (ii) large experimentally observed DN asymmetry [29], and (iii) large matter potential extracted from the data, when the best fit value of Δm^2_{21} from global fit is taken. Very light sterile neutrinos or non-standard interactions are among possible solutions [10].

3. Mass hierarchy

There are several aspects of the neutrino mass ordering.

1). Phenomenology: The type of mass hierarchy plays crucial role in (i) flavor evolution of supernova neutrinos; (ii) high energy (> 2 GeV) atmospheric neutrinos; (iii) long baseline experiments; (iv) neutrinoless double beta decay. It is relevant for Cosmology, but affects very weakly solar neutrinos.

It is believed that establishing mass hierarchy is important step forward to precise measurements of the CP-violation phase. Recent developments show, however, that CP-violation may be established first.

2). Theory: The mass spectra in two cases have a fundamental difference. In the case of NH the spectrum is similar to the one of quarks and charged leptons although with certain re-scaling: The hierarchy of neutrino masses is milder (in contrast to expectations from the seesaw), see (2.6), which can be related somehow to smallness of neutrino mass and large lepton mixing. Indeed, from neutrino sector one obtains $\theta \sim \sqrt{m_2/m_3} \approx 25^\circ$, and additional $\sim 15^\circ$ may come from the charged lepton mass matrix (although one expects a bit smaller contribution $\sqrt{m_\mu/m_\tau} \sim 10^\circ$). The NH spectrum can testify for the seesaw mechanism with special form of the RH neutrino mass matrix. It also favors the quark-lepton symmetry and grand unification.

In the case of IH two heavier mass states are strongly degenerate:

$$\frac{\Delta m_{21}}{m_2} \approx \frac{\Delta m_{21}^2}{2\Delta m_{32}^2} \approx 1.6 \cdot 10^{-2}. \tag{3.1}$$

This is not accidental and implies certain symmetry. Usually strong degeneracy is accomplished by nearly maximal mixing. However, the deviation of the 1-2 mixing from maximal is rather significant. Neutrino mass matrix can give maximal 1-2 mixing, which is then reduced by about 10° contribution from the charged lepton mixing. The spectrum can be viewed as 1 Majorana neutrino and 1 pseudo-Dirac neutrino. It may testify for flavor symmetry, e.g., broken $L_e - L_\mu - L_\tau$ lepton number.

“Race" for the mass hierarchy has started. There are 4 types of effects (observations) will be used to establish the hierarchy.

1. Matter effect on the 1-3 mixing: This, in turn, affects oscillations and adiabatic conversion. Experiments include detection of atmospheric neutrinos (PINGU, ORCA, INO, Hyper-Kamiokande); long baseline experiments (NOvA, LBNF-DUNE, JPARC-HK); studies of supernova neutrino bursts.

2. Precise measurements of Δm_{ij}^2 and tests of equalities (2.4, 2.5) will be done by middle baseline reactor experiments JUNO and RENO-50.

3. Cosmological measurements of $\sum_k m_k$.

4. Searches for the neutrinoless double beta decays.

Let us comment on the two last issues. The sensitivity of cosmological measurements and double beta decay can be best seen in terms of $\sum_i m_i$ and $m_{\beta\beta}$, where

$$m_{\beta\beta} = U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha} + U_{e3}^2 m_3 e^{i\beta}. \tag{3.2}$$

In Fig. 3 from [**?**] we show constraints from cosmological surveys and oscillations in the plane $\sum_i m_i - m_{\beta\beta}$ for two hierarchies. The cosmological constrains are taken from [12]. The gray band is the 95% C.L. excluded region coming from Cosmology. As can be seen, the upper bounds $\sum_i m_i < 0.095$ eV or/and $m_{\beta\beta} < 0.012$ eV would exclude the IH at 3σ level.

Let us consider the first item. The mass and flavor spectrum in matter differs from that in vacuum (Fig. 1) and changes with matter density. This change drastically depends on the mass hierarchy (see fig. in [30]). There are two resonance densities, L - low and H - high, given by the resonance conditions:

$$V(\rho_L) = \frac{\Delta m_{21}^2 \cos 2\theta_{21}}{2E}, \; V(\rho_H) = \frac{\Delta m_{31}^2 \cos 2\theta_{31}}{2E}. \tag{3.3}$$

The overall change of mixing pattern consists of moving of the ν_e flavor from the lowest energy level to the highest one. In the case of Normal hierarchy the change proceeds in the following way: first the amount of ν_e flavor decreases in ν_{1m} but increases in ν_{2m}. These amounts become equal in the L-resonance. Then the admixture of ν_e continues to increase in the ν_{2m} and is mostly accumulated in this state in the intermediate region between the two resonance densities $\sqrt{\rho_H \rho_L}$. Distribution of two other flavors appears in two nearly orthogonal combinations of ν_μ and ν_τ: ν_μ' and ν_τ' which participate as the whole (no redistribution within combinations). So, the combination

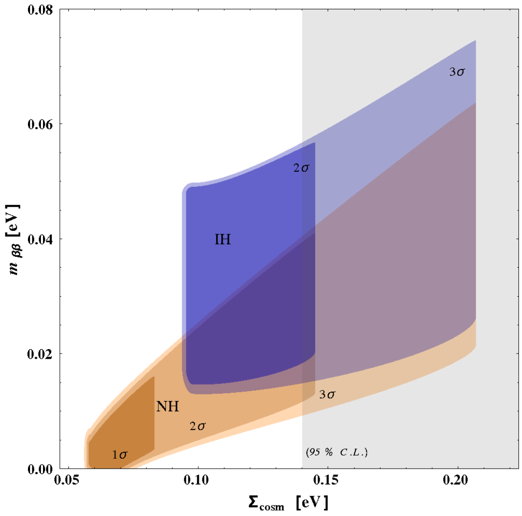

Figure 3: Allowed regions in the plane for normal and inverted mass hierarchies in the plane of effective Majorana mass of the electron neutrino (oscillation data) and sum of neutrino masses (Cosmology), from [12].

which was in the state ν_{2m} turns out to be in ν_{1m}. With approaching to the H-resonance density the ν_e flavor start to move into ν_{3m} interchanging with the combination ν'_τ. In the H-resonance ν_e is distributed equally in ν_{2m} and ν_{3m}. With further increase of density ν_e moves to ν_{3m} almost completely.

In the antineutrino channel we have opposite sign of the potential, $-V$, and therefore the ν_e flavor moves with increase of density to lower energy level, eventually accumulating in $\bar{\nu}_{1m}$.

In the case of IO ν_e flavor moves from ν_{1m} to ν_{2m}. As in the case of NO, at the density ρ_L the admixtures of ν_e in ν_{1m} and ν_{2m} become equal, thus realizing the L-resonance. The flavors states ν_e and ν'_μ are permuted (also small admixture of ν_e from the lightest level ν_{3m} moves to ν_{1m} and ν_{2m}). The difference of patterns is in the region of ρ_H where now no $H-$resonance is realized. At densities $\gg \rho_H$ the energy levels become $\nu_{2m} \approx \nu_e$ $\nu_{1m} \approx \nu'_\tau$, $\nu_{3m} \approx \nu'_\mu$. Actually the pattern is very close to that for NO: ν_e is in the highest energy level with the difference that now intermediate level is ν'_μ and the lowest one – ν'_τ. The splitting between the two lightest levels is Δm^2_{23}.

In the antineutrino channel $\bar{\nu}_e$ moves to lower energy levels. First from $\bar{\nu}_{2m}$ to $\bar{\nu}_{1m}$ (no resonance) and then from ν_{2m} to ν_{3m}. Now at ρ_H the $\bar{\nu}_e$ admixtures in $\bar{\nu}_{2m}$ and $\bar{\nu}_{3m}$ become equal realizing the H resonance. In the first approximation changing mass hierarchy is equivalent to interchange of neutrinos and antineutrinos.

Supernova neutrinos. The overall picture of transitions includes the following [31].

At distances about 100 km neutrinos can take part in collective flavor transformations due to $\nu - \nu$ scattering in the late (cooling) phase of a burst when neutrino density near the core of a star becomes comparable or larger than usual density.

In outer regions with $\rho \sim 10^4$ g/cm^3 neutrinos undergo the MSW transformations crossing two resonances. With known value of the 1-3 mixing the transformations are highly adiabatic.

At late phases in the MSW region the transformations can be affected by the shock wave propagation since the adiabaticity is broken in the front of the wave.

Neutrinos propagate between the star and the Earth as mass eigenstates without change of flavor.

The mass states entering the Earth split into eigenstates in matter and oscillate again.

All these effects (but 4.) depend on the type of mass hierarchy.

1) Shock wave breaks adiabaticity of the flavor conversion in the 1-3 resonance. This leads to softening of the spectrum of the electron neutrinos since $\nu_e \to \nu_{\mu,\tau}$ conversion becomes less efficient in certain energy interval. The interval shifts with time (during the burst) from low to high energies [32]. Observation of this effect in the neutrino (antineutrino) channel will imply normal (inverted) hierarchy.

2) Neutrino collective effects are more profound in the IH case can lead in particular to spectral split phenomena - partial or complete swaps of spectra of neutrinos of different flavors in certain energy ranges. If the spectral splits are observed at high energies, the hierarchy should be inverted [33], [34].

3) Sharp time-rise of the $\bar{\nu}_e$ flux and signal in the initial phase of neutrino burst will testify for IH [35].

4) Strong suppression of the ν_e- neutronization peak is the signature of NH. In this case $\nu_e \to \nu_3$ transition occurs and the ν_e survival probability equals $P_{ee} = \sin^2\theta_{13} \approx 0.02$, as compared to $P = \cos^2\theta_{12} \approx 0.68$ in the case of IH [36].

5) At the accretion and cooling phases the adiabatic conversion leads to partial of complete permutation of the electron and non-electron neutrino spectra. As a result, the ν_e energy spectrum (and similarly the $\bar{\nu}_e$ spectrum) becomes two-component: a mixture of the original ν_e and ν_μ spectra. Precise composition depends on the hierarchy [36], [37].

6) The Earth matter effects consist of an oscillatory modulation of the neutrino energy spectrum as well as difference of signals in detectors situated in different places of the Earth [36], [38]. These effects are due to the 1-2 mixing, but their existence depends on conversion in a star driven by the 1-3 mixing and therefore on mass hierarchy. Being observed in the antineutrino channel the effects will be evidence of NH, if they appear in the neutrino channel, IH is established. The problem here is that in the antineutrino channel, which is the most suitable for detection, the difference of original fluxes of the electron and non-electron antineutrinos is small, and consequently, the oscillation effects are small.

In the case of NH in the MSW region adiabatic conversion leads to transformations: $\nu'_\tau \to \nu_2$ $\nu'_\mu \to \nu_1$, where $\nu'_\tau \approx \nu_3$ and ν'_μ is the orthogonal combination of ν_μ, ν_τ . Inside the Earth the mass states ν_2 and ν_1 split and start to oscillate again. The effect of oscillations in a detector is given by sum of the effects of oscillations of ν_1 and ν_2 and therefore is proportional to difference of the ν'_μ and ν'_τ fluxes. No Earth matter effect can be observed if initial fluxes of ν_μ and ν_τ are identical. (Even if they are different, due to maximal 2-3 mixing the ν_μ and ν_τ.) Collective effects and shock waves effects may change this equality.

Atmospheric neutrinos oscillate in the matter of the Earth, and two effects depend on mass hierarchy (see for recent review [39]:

1) *resonance enhancement* of oscillations driven by the 1-3 mixing;

2) *parametric enhancement* of oscillations for core-crossing trajectories.

Method of determination of the hierarchy consists of (i) measurement of the $E-\theta$ distributions of events of different types; (ii) fit of the distributions in assumption of the normal or inverted orderings. Two types of events will be studied:

1). "tracks" (actually, muon tracks plus cascades) which are induced by the charged current interactions:

$$\nu_\mu + N \to \mu + h \tag{3.4}$$

$$\nu_\tau + N \to \tau + h, \quad \tau \to \mu + \nu_\mu + \nu_\tau, \tag{3.5}$$

where both muon track and hadron cascade will be detected. Furthermore, the energy and direction of muon, E_μ, θ_μ, as well as the energy of cascade, E_h, or inelasticity can be measured. Certain information about cascade direction can be obtained. Then both energy, E_ν, and direction, θ_ν, of neutrino can be reconstructed.

2) "Cascades" are induced by the ν_e- charged current interaction $\nu_e + N \to e + h$, neutral currents $\nu_\alpha + N \to \nu_\alpha + h$, $\alpha = e, \mu, \tau$ and ν_τ charged current interactions:

$$\nu_\tau + N \to \tau + h, \quad \tau \to e + \nu_e + \nu_\tau, \quad \to h + \nu_\tau. \tag{3.6}$$

For these events characteristics of electron and hadron cascades will be measured.

There is recent serious progress in the volume detection technique. In particular, using time information about development of cascades it is possible to reconstruct direction of original electron or hadron with rather good angular resolution. Also, it seems, the cascades produced by electron and hadrons can be distinguished to some extent.

Including inelasticity of the CC ν_μ events in analysis [40] will further improve the sensitivity.

The "Distinguishability metric", can be used as quick estimator of sensitivity [41]. In a small bin in the $(E-\theta)$ plane one can compute number of events in the case of NH and IH and introduce asymmetry

$$S_{ij} = \frac{N_{ij}^{IH} - N_{ij}^{NH}}{\sqrt{N_{ij}^{NH}}}. \tag{3.7}$$

The denominator is a kind of statistical error, so that $|S|$ reflects statistical significance of distinguishing normal and inverted mass hierarchies. The S_{ij} distribution obtained for neutrino energies and direction should be smeared over the experimental energy and angular reconstruction functions. The distribution for the tracks and cascades (computed for PINGU) are shown in Fig. 4 (from [8])

The key features of the distributions are the following.

1. In the track distribution, appearance of the peak at $E = (7-14)$ GeV and $|\cos\theta_Z| = 0.50 - 0.85$ is due to the MSW resonance in 1-3 channel.

2. In the cascades distribution: there is the profound deep, $S < 0$, at lower energies $E = (5-12)$ GeV and larger angles $|\cos\theta_Z| = 0.7 - 1.0$. The difference from the track case originates large contribution from parametric enhancement of oscillations for the core crossing trajectories. Significant peak ($S > 0$) appears for outer trajectories with $|\cos\theta_Z| = 0.2 - 0.4$.

3. The S from cascades is about 2 times larger than S from tracks (see explanatory bars in the figures). Also S for cascades and tracks have opposite signs (see explanation in [41]). Therefore, the flavor identification is crucial.

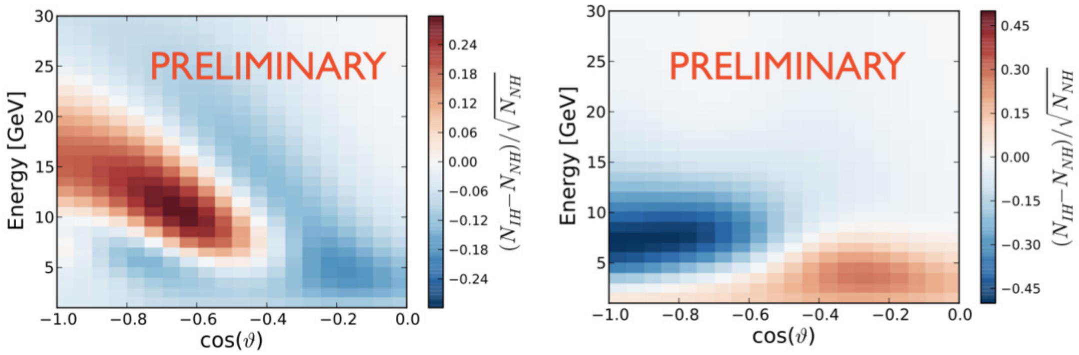

Figure 4: S-distributions of the track (left) and cascade (right) events smeared over the neutrino energy and zenith angle reconstruction functions, from [8].

Total (integrated over all the bins) distinguishability is defined as

$$S_{tot} = \sqrt{\sum_{ij} |S_{ij}|^2}. \tag{3.8}$$

PINGU [42] and ORCA [43] experiments will measure these S-distributions. PINGU - Precision IceCube Next Generation Upgrade will have 40 strings with 96 DOM's (Digital Optical Modules) per string according to [8]. This will provide multi-megaton effective volume (mass) at $E > 3$ GeV. Sensitivity of PINGU to the mass ordering (with tracks and cascades added) as function of time is shown in Fig. 5. The 3σ identification of hierarchy will be possible after 3.5 years of operation. The 4σ confidence level would require about 10 years. The identification is slightly better in the case of true normal hierarchy. There are various ways to further enhance sensitivity, e.g., use the 3D distributions including inelasticity.

PINGU as well as ORCA can address other important issues. In particular, measurements of deviation of the 2-3 mixing from maximal. This is crucial for understanding symmetry behind the lepton mixing. Fig. 2 (right) shows the present and future sensitivities to the parameters of 2-3 sector. If true value is $\sin^2\theta_{23} = 0.45$, the 90% CL interval after 3 years of PINGU operation can be 0.45 ± 0.03, *etc*. The errors are 1.5 - 2 times smaller than the projected errors of T2K or NOvA. Furthermore, due to large matter effect PINGU sensitivity to the octant of the 2-3 mixing will be substantially higher than the one of NOvA. Updated proposal is under preparation.

ORCA - Oscillation Research with Cosmics in the Abyss (actually in Mediterranean) will consist (according to the present design [43], [44]) 115 lines with 20 m spacing, so that the radius of detector is about 107 m. Each line will have 18 DOM's (optical modules) spaced by 6 - 9 m (2070 DOM in total). Instrumented volume is about 3.8 Mt. Each DOM contains 31 3-inch PMT's which will ensure wide angle view [44].

Sensitivity of ORCA to MH as function of time is similar (see Fig. 5) to PINGU one. The sensitivity increases with θ_{23}, especially for NH. Identification of the hierarchy in the second octant is easier than first octant [46]. When fixing δ_{CP} to zero, the sensitivity increases by $\sim 0.5\sigma$. Effects of CP is stronger for IH. The first ORCA test facility will be deployed in 2016.

INO-ICAL is the 50 kt magnetized iron calorimeter (ICAL) at the India-based Neutrino Observatory (INO) [47]. The main element of the detector is resistive plate chambers. Measurable

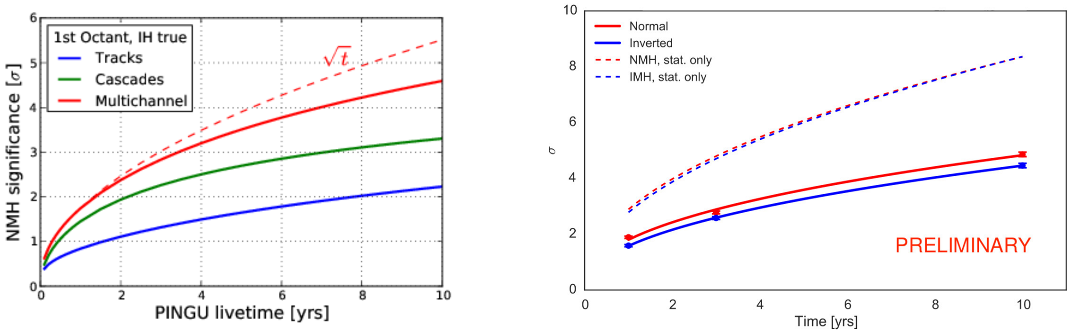

Figure 5: Sensitivity of PINGU (left) from [8] and ORCA (right) [44] [45] to mass hierarchy.

characteristics include energy and direction of muons, energy of multi-GeV hadrons, and sign of the charge of muon. The energy and zenith angle dependence of the atmospheric neutrinos in the multi-GeV range will be reconstructed. For fixed oscillation parameters (assuming that precision of their determination will be high enough) 3σ C.L. establishing of the NH will be possible after 11 years of operation.

4. CP-violation

There are various predictions of the phase δ_{CP}. Specific values of δ_{CP} like 0, π , $\pi/2$ may have straightforward and suggestive implications (still not unique) for theory. Thus, values $\pm\pi/2$ can be related (by symmetry) with maximal 2-3 mixing, quasi-degenerate mass states, *etc*. Comparison with the quark phase will be important since even in the unification approach they can be very different.

Interesting results on the CP-phase can be obtained in the framework (2.10). If U_{CKM} is the only source of CP violation and no CP violation exists in U_X, the equality (2.10) leads to the following relation [26]

$$\sin\theta_{13}\sin\delta_{CP} = (-\cos\theta_{23})\sin\theta_{13}^{q}\sin\delta^{q}. \tag{4.1}$$

Here the quark phase equals $\delta^q = -0.2\pi$, when the quark mixing is reduced to the same parametrization as the lepton one. According to (4.1) $\sin\delta_{CP} \sim \lambda^3/s_{13} \sim \lambda^2$. That is, $\delta_{CP} \approx -\delta$, or $\pi + \delta$, where $\delta \equiv (s_{13}^q/s_{13})c_{23}\sin\delta^q$ is small. There are two important implications of this result:

1. If the observed value of δ_{CP} deviates substantially from 0 or π, new sources of CP violation should exist in the lepton sector beyond CKM.

2. New sources of CP violation originating from U_X may have specific symmetries that lead to particular values of δ_{CP}, e.g. $-\pi/2$.

Let us consider perspectives of experimental determination of CP-phase. Presently the global fit gives 2 σ preference of the phase $3\pi/2$ with respect to 0 [3]. Maximally disfavored value of the phase is $\pi/2$. Sensitivity to the phase mainly comes from results of T2K and reactor experiments on 1-3 mixing. The projected sensitivity of running experiments has been estimated [48]. J-PARC beam upgrade will provide $7.8\cdot 10^{21}$ p.o.t. by 2018, i.e. by factor 12 larger than now. (Presently J-PARC runs in the antineutrino mode, and due to smaller cross-section the increase of sensitivity will be modest). With this statistics the sensitivity to δ_{CP} at 90% C.L. or better is expected e.g.

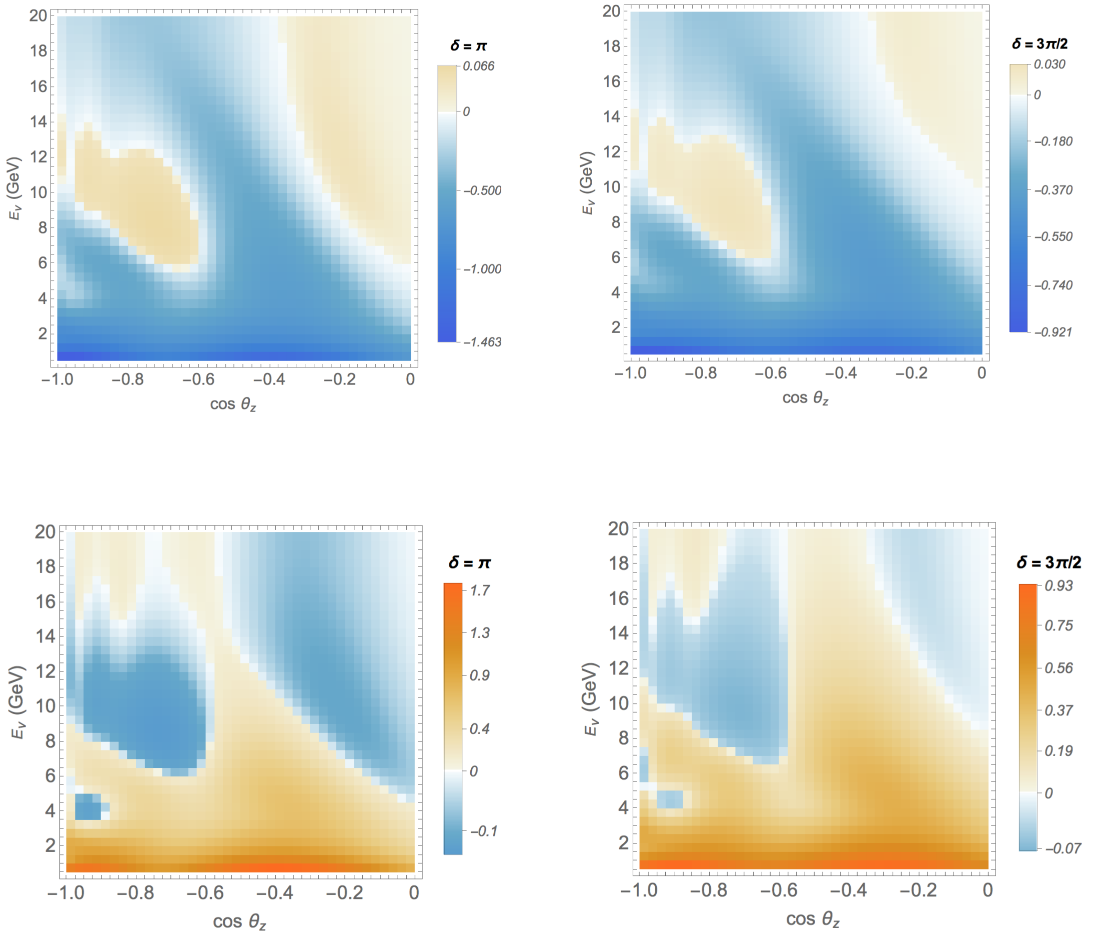

Figure 6: Distribution of the relative CP differences, S_{ij}, for $\nu_\mu + \bar{\nu}_\mu$ events in the $E_\nu - \cos\theta_z$ plane after 1 year of Super-PINGU exposure. The distributions are smeared over the energy and zenith angle of neutrinos. The smearing functions have been taken in the form of the PINGU reconstruction functions with widths reduced by factor $1/\sqrt{3}$. From [52].

over $-115^\circ < \delta_{CP} < -60^\circ$ for NH and $50^\circ < \delta_{CP} < 130^\circ$ for IH if $\theta_{23} = 45^\circ$ [48]. Uncertainty in θ_{23} reduces the sensitivity. The first NOvA result announced recently also favors maximal CP-violation. So, it may happen that with all available by 2018- 2020 data (J-PARC- SK plus NOvA plus reactors) values of the phase $3\pi/2$ and 0 can be distinguished at more than 3σ level.

Future dedicated experiment J-PARC- HK [49] , LBNF-DUNE [50], ESS (European spallation source, Lund) [51] can achieve $\approx (5-7)\sigma$ discrimination between $3\pi/2$ and 0 in 2030 - 2035. In view of these long term and expensive commitments all possible alternatives to measure δ_{CP} must be explored, and various scenarios of developments in the next 20 years should be considered.

In PINGU and ORCA the CP-violation effects are subleading ones, which actually helps to identify the mass hierarchy without significant degeneracy with δ_{CP}. According to ORCA simulations 3σ determination of hierarchy is affected (reduced) by about 0.5σ due to the CP phase uncertainty [46, 44].

Assuming that the hierarchy is known one can explore a possibility to use again the atmo-

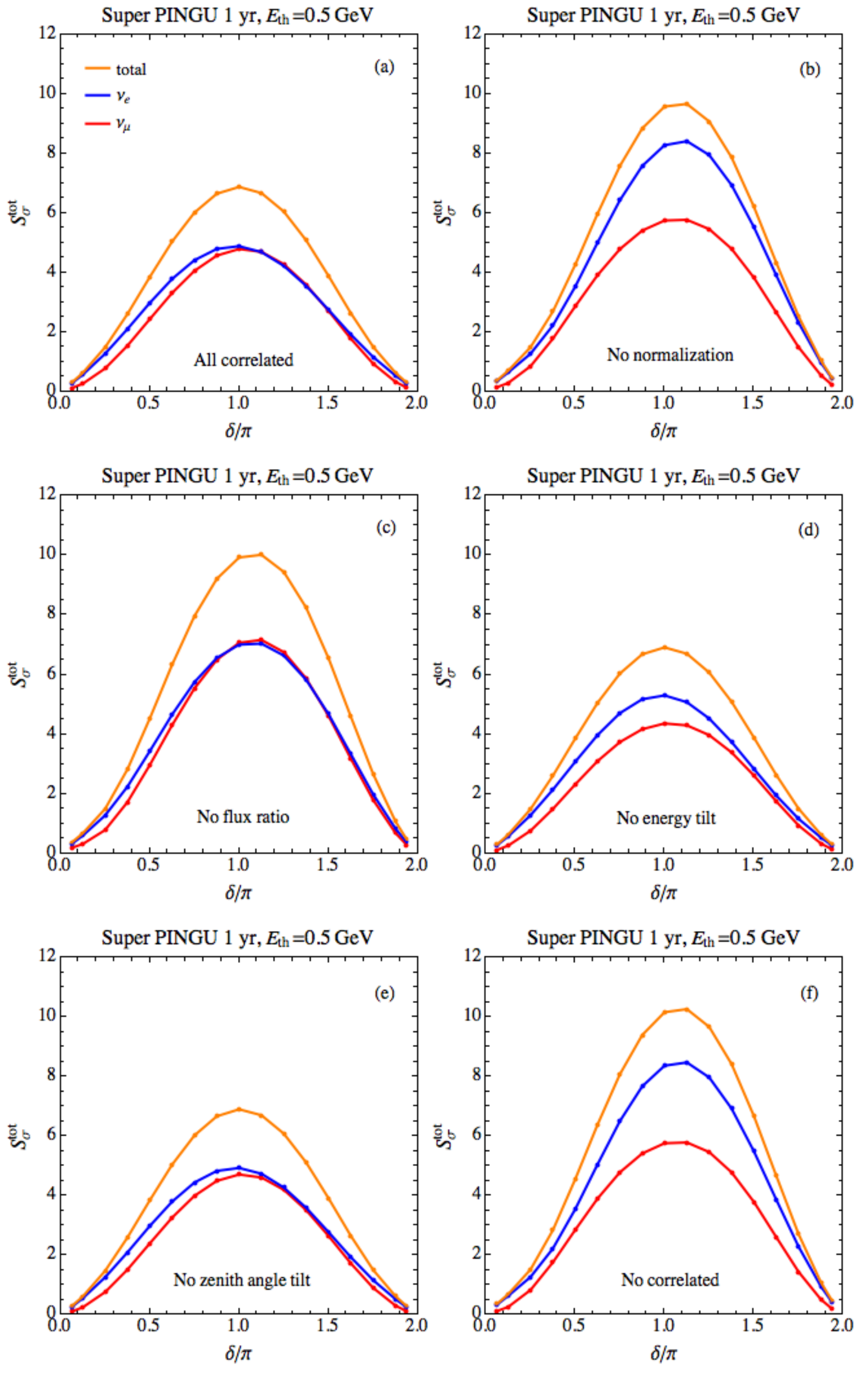

Figure 7: Effects of different correlated systematic errors on sensitivity to the CP-phase. Shown are the total distinguishability as well as integrated Super-PINGU distinguishabilities from ν_μ and ν_e events between a given value of δ and $\delta = 0$ as functions of δ. Different panels correspond to the cases when (a) all errors are included; (b) normalization uncertainty of 20% is removed; (c) flux ratio uncertainty is removed; (d) the energy tilt uncertainty is removed; (e) the angular tilt uncertainty is removed; (f) all correlated systematic uncertainties are removed. The distinguishabilities have been computed after smearing, with 2.5% uncorrelated systematics 1 year exposure, $E_{th} = 0.5$ GeV and for sum of ν and $\bar{\nu}$ signals. From [52].

spheric neutrinos and upgrades of PINGU and ORCA to measure δ_{CP} [52]. The key condition for this is to further reduce the energy threshold down to (0.5 - 1) GeV. It has been shown [52] that in spite of averaging of oscillations driven by the 1-3 mass splitting, the CP violation effect does not disappear and actually increases with decrease of energy. The δ_{CP} effect on the probability is about 10% below 1.5 GeV. With change of δ_{CP} the probabilities increase or decrease in large interval of energies and zenith angles (lengths of trajectories) in the same way. Therefore, even poor angular resolution does not vanish sensitivity to the phase.

The CP phase effect has opposite sign for $\nu_\mu - \nu_e$ and $\nu_\mu - \nu_\mu$ transitions. Therefore, the flavor identification is crucial. Also the CP effect has opposite signs for neutrinos and antineutrinos. So, an effective separation of the neutrino and antineutrino signals (which can be partially done using inelasticity [40]) would enhance the sensitivity. Clearly, better energy and angular resolutions will help, also reducing effects of systematics.

Notice that the Megaton-scale Ice Cherenkov Array (MICA) [53] has been considered as future development of the volume detection technique with the effective energy threshold about 10 MeV. The goal is to detect the supernova neutrinos and possibly the high energy part of the solar neutrino spectrum. The Super-PINGU, or Super-ORCA for CP measurements could be an intermediate step between PINGU- ORCA and MICA.

We can use the CP distinguishability (analogy of the hierarchy distinguishability) to estimate the discovery potential. For the energy-zenith angle ($E_\nu - \cos\theta_z$) bin, ij, we define the relative CP-difference [52]

$$S_{ij} = \frac{N_{ij}^{\delta_{CP}} - N_{ij}^{\delta_{CP}=0}}{\sqrt{N_{ij}^{\delta_{CP}=0}}}. \tag{4.2}$$

If $\delta_{CP} = 0$ is the true value of the phase, then $N^{\delta_{CP}=0}$ can be considered as the "experimental" number of events, whereas δ_{CP} and $N_{ij}^{\delta_{CP}}$ can be treated as the "fit" value of phase and fit number of events. Then $|S_{ij}|$ can be interpreted as statistical significance of distinguishing a given value δ_{CP} from $\delta_{CP} = 0$. The quantity S does not take into account fluctuations. Still S_{ij} is very useful characteristic which allows one to study dependence of the discovery potential on various parameters. The uncorrelated systematic errors can be added to the denominator of (4.2) as

$$N_{ij}^{\delta_{CP}=0} \to \sigma_{ij}^2 = N_{ij}^{\delta_{CP}=0} + (f N_{ij}^{\delta_{CP}=0})^2, \tag{4.3}$$

where f determines the level of systematic errors. If measurements in each bin are independent (which is realized after smearing), the total significance is given by

$$S_{tot} = \sqrt{\sum_{ij} |S_{ij}|^2}. \tag{4.4}$$

The S-distributions of the ν_μ (tracks) and ν_e (cascade) events for values of $\delta_{CP} = \pi$ and $3\pi/2$ smeared over neutrino energy and direction are shown in Figs. 6. In fig. 7 the integrated distinguishability is presented as function of δ_{CP} after 1 year of exposure with various systematic errors included. Flavor mis-identification can further reduce distinguishability by factor 1.5 - 2. Still $S_\sigma \approx 3-4$ can be achieved for $\delta = \pi$ after 4 years of exposure.

Notice that maximal difference from $\delta_{CP} = 0$ is for $\delta_{CP} = \pi$ and not for maximal CP-violation in contrast to accelerator method based on comparison of the neutrino and antineutrino signals.

So, studies of CP violation with atmospheric neutrinos are complementary to those with the beam measurements.

5. Summary

Enormous progress has been achieved in neutrino physics in last 15 years: all mixing angles and mass splittings in the 3ν framework are measured with better than 10% accuracy. Still physics behind the neutrino mass and mixing is not identified. Few challenges or anomalies imply existence of new neutrino states - sterile neutrinos, and furthermore the eV scale steriles are not small perturbations of the 3ν framework.

Measurements of missing parameters of the 3ν paradigm - mass hierarchy, CP phase, as well as searches physics beyond the 3ν paradigm will drive future progress.

Identification of the neutrino mass ordering is the next big in neutrino physics. Race for the mass hierarchy has started with main actors being PINGU, ORCA, JUNO, RENO 50, NOvA, Supernova neutrinos, $\beta\beta_{0\nu}$ decays Cosmology. One expect the decisive results by 2025 - 2026. Detection of the Galactic supernova burst may give an answer earlier. (The latter require, however, better understanding collective effects and the produced spectra of neutrinos.)

Large atmospheric neutrino detectors with low (few GeV) energy threshold, PINGU and ORCA, may turn out to be first in this race. In this connection fast developments of the volume detection techniques of low energy neutrinos in multi-Megaton scale detectors occur now.

Measurements of the Dirac CP-phase is ultimate goal in oscillation neutrino experiments. A possibility to use further upgrades of PINGU, ORCA detectors to measure the CP phase should be explored. These upgrades can address crucial issues in particle and neutrino physics: establishing neutrino mass ordering, determination of the CP-phase, searches for sterile neutrinos, searches for non-standard neutrino interactions, *etc*.

With recent developments (NOvA results) it may happen that CP-violation can be established even earlier than it was expected changing future strategy of research.

Acknowledgement

I would like to thank the organizers of the Conference for their hospitality.

References

[1] P. F. Harrison, D. H. Perkins and W. G. Scott, Phys. Lett. B **530** (2002) 167 [hep-ph/0202074].

[2] Y. Farzan, Phys. Lett. B **748** (2015) 311 [arXiv:1505.06906 [hep-ph]].

[3] M.C. Gonzalez-Garcia, M. Maltoni, T. Schwetz, JHEP 1411 (2014) 052, [1409.5439 [hep-ph]], D. V. Forero, M. Tortola and J. W. F. Valle, Phys. Rev. D **90** (2014) 9, 093006 [arXiv:1405.7540 [hep-ph]], F. Capozzi, G. L. Fogli, E. Lisi, A. Marrone, D. Montanino and A. Palazzo, Phys. Rev. D **89** (2014) 093018 [arXiv:1312.2878 [hep-ph]].

[4] F. P. An *et al.* [Daya Bay Collaboration], arXiv:1505.03456 [hep-ex].

[5] J. K. Ahn *et al.* [RENO Collaboration], Phys. Rev. Lett. **108** (2012) 191802 [arXiv:1204.0626 [hep-ex]], J. H. Choi *et al.* [RENO Collaboration], arXiv:1511.05849 [hep-ex].

[6] Y. Abe *et al.* [Double Chooz Collaboration], JHEP **1410** (2014) 086 [JHEP **1502** (2015) 074] [arXiv:1406.7763 [hep-ex]].

[7] M. G. Aartsen *et al.* [IceCube Collaboration], Phys. Rev. D **91** (2015) 7, 072004 [arXiv:1410.7227 [hep-ex]].

[8] K. Clark, these Proceedings.

[9] S. Abe *et al.* [KamLAND Collaboration], Phys. Rev. Lett. **100** (2008) 221803 [arXiv:0801.4589 [hep-ex]].

[10] M. Maltoni and A. Y. Smirnov, arXiv:1507.05287 [hep-ph].

[11] K. Abe *et al.* [T2K Collaboration], Phys. Rev. D **91** (2015) 7, 072010 [arXiv:1502.01550 [hep-ex]].

[12] S. Dell'Oro, et al, 1505.02722 [hep-ph].

[13] S. Mertens [KATRIN Collaboration], Phys. Procedia **61** (2015) 267.

[14] P. Minkowski, Phys. Lett. B **67** (1977) 421; T. Yanagida, in Proc. of Workshop on Unified Theory and Baryon number in the Universe, eds. O. Sawada and A. Sugamoto, KEK, Tsukuba, (1979); M. Gell-Mann, P. Ramond and R. Slansky, in Supergravity, eds. P. van Niewenhuizen and D. Z. Freedman (North Holland, Amsterdam 1980); S. L. Glashow, in Quarks and Leptons, Cargese lectures, eds M. Levy, (Plenum, 1980, New York) p . 707; R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44**, (1980) 912.

[15] R. N. Mohapatra, Phys. Rev. Lett. **56** (1986) 561; R. N. Mohapatra and J. F. W. Valle, Phys. Rev. D **34** (1986) 1642.

[16] S. B. Roland, B. Shakya and J. D. Wells, arXiv:1412.4791 [hep-ph], S. B. Roland, B. Shakya and J. D. Wells, Phys. Rev. D **92** (2015) 9, 095018 doi:10.1103/PhysRevD.92.095018 [arXiv:1506.08195 [hep-ph]].

[17] L. Canetti, M. Drewes, T. Frossard and M. Shaposhnikov, Phys. Rev. D **87** (2013) 093006 [arXiv:1208.4607 [hep-ph]].

[18] E. Bulbul, M. Markevitch, A. Foster, R. K. Smith, M. Loewenstein and S. W. Randall, Astrophys. J. **789** (2014) 13 [arXiv:1402.2301 [astro-ph.CO]], A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi and J. Franse, Phys. Rev. Lett. **113** (2014) 251301 [arXiv:1402.4119 [astro-ph.CO]], A. Boyarsky, J. Franse, D. Iakubovskyi and O. Ruchayskiy, Phys. Rev. Lett. **115** (2015) 161301 [arXiv:1408.2503 [astro-ph.CO]].

[19] T. E. Jeltema and S. Profumo, arXiv:1512.01239 [astro-ph.HE].

[20] M. Anelli *et al.* [SHiP Collaboration], arXiv:1504.04956 [physics.ins-det], S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph].

[21] A. Ghalsasi and A. E. Nelson, Phys. Rev. D **90** (2014) 4, 045002 [arXiv:1405.0711 [hep-ph]]. C. Wetterich, Nucl. Phys. B **897** (2015) 111 [arXiv:1408.0156 [hep-th]].

[22] G. Altarelli and F. Feruglio, Rev. Mod. Phys. **82** (2010) 2701 [arXiv:1002.0211 [hep-ph]], F. Feruglio, Eur. Phys. J. C **75** (2015) 8, 373 [arXiv:1503.04071 [hep-ph]], S. F. King, A. Merle, S. Morisi, Y. Shimizu and M. Tanimoto, New J. Phys. **16** (2014) 045018 [arXiv:1402.4271 [hep-ph]].

[23] C. Giunti and M. Tanimoto, Phys. Rev. D **66**, 053013 (2002) [hep-ph/0207096].

[24] H. Minakata and A. Y. Smirnov, Phys. Rev. D **70** (2004) 073009 [hep-ph/0405088].

[25] Z. z. Xing, Phys. Lett. B **618** (2005) 141 [hep-ph/0503200]; S. Antusch and S. F. King, Phys. Lett. B **631** (2005) 42 [hep-ph/0508044].

[26] B. Dasgupta and A. Y. Smirnov, Nucl. Phys. B **884** (2014) 357 [arXiv:1404.0272 [hep-ph]].

[27] P. O. Ludl and A. Y. Smirnov, Phys. Rev. D **92** (2015) 7, 073010 doi:10.1103/PhysRevD.92.073010 [arXiv:1507.03494 [hep-ph]].

[28] A. Esmaili, F. Halzen and O. L. G. Peres, JCAP **1307** (2013) 048 [arXiv:1303.3294 [hep-ph]], A. Esmaili and A. Y. Smirnov, JHEP **1312** (2013) 014 [arXiv:1307.6824 [hep-ph]].

[29] Super-Kamiokande collaboration (Renshaw, A. et al.) Phys.Rev.Lett. 112 (2014) 091805 arXiv:1312.5176.

[30] A. Y. Smirnov, PoS Neutel **2013** (2014) 027 [arXiv:1312.7309 [hep-ph]].

[31] A. Mirizzi, I. Tamborra, H. T. Janka, N. Saviano, K. Scholberg, R. Bollig, L. Hudepohl and S. Chakraborty, arXiv:1508.00785 [astro-ph.HE].

[32] R. Tomas, M. Kachelriess, G. Raffelt, A. Dighe, H.-T. Janka and L. Scheck, JCAP **0409** (2004) 015 [astro-ph/0407132].

[33] H. Duan, G. M. Fuller, J. Carlson and Y. Z. Qian, Phys. Rev. Lett. **99** (2007) 241802 [arXiv:0707.0290 [astro-ph]].

[34] B. Dasgupta, A. Dighe, G. G. Raffelt and A. Y. Smirnov, Phys. Rev. Lett. **103** (2009) 051105 [arXiv:0904.3542 [hep-ph]].

[35] P. D. Serpico, S. Chakraborty, T. Fischer, L. Hudepohl, H. T. Janka and A. Mirizzi, Phys. Rev. D **85** (2012) 085031 [arXiv:1111.4483 [astro-ph.SR]].

[36] A. S. Dighe and A. Y. Smirnov, Phys. Rev. D **62** (2000) 033007 [hep-ph/9907423], M. Kachelriess, R. Tomas, R. Buras, H.-T. Janka, A. Marek and M. Rampp, Phys. Rev. D **71** (2005) 063003 [astro-ph/0412082].

[37] C. Lunardini and A. Y. Smirnov, JCAP **0306** (2003) 009 doi:10.1088/1475-7516/2003/06/009 [hep-ph/0302033].

[38] C. Lunardini and A. Y. Smirnov, Nucl. Phys. B **616** (2001) 307 doi:10.1016/S0550-3213(01)00468-0 [hep-ph/0106149].

[39] M. Blennow and A. Y. Smirnov, Adv. High Energy Phys. **2013** (2013) 972485 [arXiv:1306.2903 [hep-ph]].

[40] M. Ribordy and A. Y. Smirnov, Phys. Rev. D **87** (2013) 113007 [arXiv:1303.0758 [hep-ph]].

[41] E. K. Akhmedov, S. Razzaque and A. Y. Smirnov, JHEP **1302** (2013) 082 [JHEP **1302** (2013) 082] [Erratum-ibid. **1307** (2013) 026] [arXiv:1205.7071 [hep-ph]].

[42] M. G. Aartsen *et al.* [IceCube PINGU Collaboration], arXiv:1401.2046 [physics.ins-det]. D. J. Koskinen, Mod. Phys. Lett. A **26** (2011) 2899.

[43] P. Coyle *et al. Km3Net Contribution to the European Strategy Preparatory Group Symposium.* September 2012, Krakow, Poland.

[44] J. Brunner, these Proceedings.

[45] C. James, these Proceedings.

[46] Martijn Jongen, these Proceedings.

[47] S. Ahmed *et al.* [ICAL Collaboration], arXiv:1505.07380 [physics.ins-det].

[48] K. Abe *et al.* [T2K Collaboration], PTEP **2015** (2015) 4, 043C01 [arXiv:1409.7469 [hep-ex]].

[49] K. Abe, T. Abe, H. Aihara, Y. Fukuda, Y. Hayato, K. Huang, A. K. Ichikawa and M. Ikeda *et al.*, *Letter of Intent: The Hyper-Kamiokande Experiment — Detector Design and Physics Potential —,* arXiv:1109.3262 [hep-ex].

[50] C. Adams *et al.* [LBNE Collaboration], arXiv:1307.7335 [hep-ex].

[51] E. Baussan *et al.* [ESSnuSB Collaboration], Nucl. Phys. B **885** (2014) 127 [arXiv:1309.7022 [hep-ex]].

[52] S. Razzaque and A. Y. Smirnov, JHEP **1505**, 139 (2015) [arXiv:1406.1407 [hep-ph]].

[53] S. Boser, M. Kowalski, L. Schulte, N. L. Strotjohann and M. Voge, Astropart. Phys. **62** (2015) 54 [arXiv:1304.2553 [astro-ph.IM]].